Optical Approaches to Quantum Information Processing and Quantum Computing

A Quantum Information Science and Technology Roadmap

Part 1: Quantum Computation

Section 6.5

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List of Acronyms and Abbreviations

C-NOT	controlled-not (gate)	QIP	quantum information processing
DFS	decoherence-free subspace	QED	quantum electrodynamics
GHZ	Greenberger, Horne, and Zeilinger	SPD	single-photon detector
HOM	Hong, Ou, and Mandel	SPS	single-photon source
KLM	Knill, Laflamme, and Milburn	SPDC	spontaneous parametric down conversion
LOQC	linear-optics quantum computing	TEP	Technology Experts Panel
QC	quantum computation/computing		

1.0 Groups Pursuing This Approach

Note: This document constitutes the most recent draft of the Optical detailed summary in the process of developing a roadmap for achieving quantum computation (QC). Please submit any revisions to this detailed summary to Todd Heinrichs (tdh@lanl.gov) who will forward them to the relevant Technology Experts Panel (TEP) member. With your input can we improve this roadmap as a guidance tool for the continued development of QC research.

Table 1-1
Optical QC Research

Research Leader(s)	Research Location
Bouwmeester, D.	**U. of California, Santa Barbara, USA**
DeMartini, F.	**Rome U., Italy**
Dowling, J.	**JPL, California, USA**
Franson, J. D.	**John Hopkins, Maryland, USA**
Gisin, N.	**U. of Geneva, Switzerland**
Howell, J. C.	**U. of Rochester, New York, USA**
Imamoglu, A.	**U. of California, Santa Barbara, USA**
Kwiat, P. G.	**U. of Illinois, Urbana-Champaign, USA**
Milburn, G. J. and Ralph, T. C.	**U. of Queensland, Australia**
Nakamura, J.	**NEC, Tskuba, Japan**
Rarity, J.	**U. of Bristol, UK**
Sergienko, A. V.	**Boston U., Massachusetts, USA**
Shih, Y. H.	**UMBC, Maryland, USA**
Steinberg, A.	**U. of Toronto, Canada**
Takeuchi, S.	**Hokkaido U., Japan**
Walmsley, I.	**U. of Oxford, UK**
Weinfurter, H.	**U. of Munich, Germany**
White, A. G.	**U. of Queensland, Brisbane Australia**
Yamamoto, Y.	**Stanford U., California, USA**
Zeilinger, A.	**U. of Vienna, Austria**
A European collaboration (RAMBOQ)*	**John Rarity (coordinator), U. of Bristol**

* This collaboration has been funded in the current round of the FET QIPC scheme of the European Commission.

2.0 Background and Perspective

Optical implementations of qubits have played an important role for quantum information science. In addition to their successful application for experimentally realizing quantum cryptography [1], photonic qubits have been among the first physical systems to enable the realization of multiparticle entanglement [2,3,4,5,6], quantum-state [7,8] and quantum-process tomography [9,10,11,12,13,14], teleportation [15,16,17,18,19,20], decoherence-free subspaces (DFSs) [21,22], and even simple quantum algorithms [23,24,25,26,27,28]. Photons have an intrinsic lack of decoherence, as well as an extreme precision with which they may be controlled using standard off-the-shelf components. For these reasons, optical qubits have played, and will continue to play, an important role in investigating foundations of quantum information processing (QIP), and fundamentals of QC in systems with small numbers of qubits. Photonic qubits for QC are particularly attractive because they could interface immediately to various quantum-communication applications (e.g., distributed QC).

Due to the extremely small photon-photon coupling available in existing materials, it was at one point believed that optical qubits could never be used for scalable QC. However, recent advances with slow light [29,30,31] and "stopped" light [32,33] indicate that these limitations may be overcome [34]. In addition, interesting results have appeared, which indicate that light which is initially prepared in a nonclassical "squeezed" state may enable additional gains for QIP (so called "continuous variable" encoding) [35,36]. Finally, it is now understood that the process of photo detection itself can lead to effective photon-photon nonlinearities [37]. For example, it has been shown in the Knill, Laflamme, and Milburn (KLM) scheme [38] that deterministic single-photon sources (SPSs) and high-efficiency single-photon detectors (SPDs) may be used to realize scalable QC with only linear optical elements. Below, we concentrate on this scheme as an example of optical QC. However, it should be emphasized that other approaches are also being followed, and may be critical for the overall progress toward scalable QC, even if these other approaches do not themselves realize it. For example, hybrid schemes involving qubits, qudits, and continuous variables, as can be realized in optical systems, have interesting and important properties—some of them display "hyper-entanglement" (simultaneous entanglement in multiple degrees of freedom), which may facilitate certain tasks in quantum information processing [39,40], such as purification and quantum error correction. Similarly, optical systems can be used to explicitly study decoherence in a controlled manner and to implement proposals for avoiding the negative effects of decoherence (e.g., DFSs). It is a feature of optically encoded qubits that decoherence can be controllably introduced by artificially coupling the qubit to other degrees of freedom [21]. This feature allows optically based systems to simulate other qubit realizations in a very clean, controllable way.

Linear optics quantum computing (LOQC) is a scheme for QIP using linear optics, SPSs, and SPDs [38]. A number of authors have suggested simplifications and modifications of the original scheme [41,42,43,44]. We take a broader view of optical QC that may also include nonlinear elements as a crucial component, provided those nonlinear elements are readily available or under development (e.g., entangled state via spontaneous parametric down conversion [SPDC], quantum memories, etc.). A number of simple experiments have been done to test the most elementary components of the scheme [45,46,47,48,49]. All of these use SPDC sources which require that experiments be done in a post-selective manner using multicoincidence detection. Further progress in the KLM scheme will require on-demand SPSs and very efficient discriminating SPDs. One of the main challenges in an LOQC approach may be the generation of the required entangled ancilla states. This becomes especially difficult if the detector efficiency is low (less than 99%). Hence, development of entanglement sources could play a key role in achieving LOQC. In addition, other alternative schemes (not based on single-photon states) have been proposed [36,50].

3.0 Summary of Optical QC: The DiVincenzo Criteria

Note: For the five DiVincenzo QC criteria and the two DiVincenzo QC networkability criteria (numbers six and seven in this section), the symbols used have the following meanings:

a) 🟢 = a potentially viable approach has achieved sufficient proof of principle;

b) 🟠 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle; and

c) 🔴 = no viable approach is known.

1. A scalable physical system with well-characterized qubits 🟠

   1.1 Qubits in the KLM scheme are represented by single-photon occupation of one mode of a pair of optical modes (dual rail logic). The two modes can be polarization modes. Other schemes using the state of a single mode are possible (e.g., coherent-state encoding represents different logical states with different coherent amplitudes in a single mode and single-mode photon number state codes also exist).

2. The ability to initialize the state of the qubits to a simple fiducial state 🟠

   2.1 Initialization of the qubits requires fast, reliable, periodic (on-demand) SPSs. Each pulse must contain one and only one photon. It must be possible to demonstrate nonclassical interference (e.g., a Hong, Ou, and Mandel [HOM] interferometer [51]) between two single-photon pulses.

3. Long (relative) decoherence times, much longer than the gate-operation time 🟢

   3.1 Single-qubit gate times are determined by the time it takes light to pass through an optical element, typically less than a picosecond. Two-qubit gate times depend on the time taken to implement a teleportation protocol. Some of these gates have been demonstrated in a post-selected mode, or conditional mode, but gates “on-demand” have not yet been demonstrated. Typically, these gates would operate on the order of nanoseconds. At optical frequencies, the effective temperature of the electromagnetic environment is zero $kT << \hbar\omega$). However, although the coupling of the qubits to the thermal environment is weak, photons are easily lost to the system. Imperfect optical elements (e.g., beam splitters, waveplates, and phase shifters) are possible sources of decoherence, and these effects have yet to be completely determined. Imperfect mode matching, which is formally equivalent to photon loss, is a more serious problem. Sources of decoherence or error are:

   - interferometric stability,
   - mode matching (both spatial and temporal),
   - photon loss, and
   - detector accuracy and efficiency.

   The error probability per gate can be estimated by examining the extent to which current interferometers can be stabilized and mode matched. With current technology this is approximately 0.1% for one-photon interference and 1% for two-photon interference. The photon loss per gate can be made less than 0.001. Preliminary calculations indicate that source and detector inefficiencies have a similar effect on the net gate fidelity [52]. These will need to be better than 99% for a fault-tolerant implementation, which is beyond the reach of current devices.

If gates are realized in terms of optical-fiber couplers or planar-integrated optical devices, mode-matching stability will be better than free-space devices; however, losses in the devices and at interfaces may be more of an issue and will still need to be minimized.

4. A universal set of quantum gates 🟠

4.1 Single-qubit operations are performed by linear elements such as beam splitters, polarization rotators, and phase shifters. Two-qubit interactions are induced conditionally by measurement of photon number in LOQC. However, teleportation gates will require very fast electro-optic control systems or photon storage. Solutions in this area will have direct relevance to current problems in conventional photonic switching technologies for optical communication systems.

4.2 Methods for generating prior entanglement are available with current technology, though not for producing entanglement on demand. Prior entanglement is useful for implementing particular error-correction codes, and may also be a method to substantially reduce gate complexity. In the long term, integrated optical devices and elementary interferometer modules will need to be developed to replace currently bulky elements. For example, a planar optical waveguide could be used to replace the four-port beam splitters used in the KLM scheme. Such devices could be made highly compact using photonic band-gap techniques and integration with SPSs.

5. A qubit-specific measurement capability 🟠

5.1 Fault-tolerant implementation of LOQC requires high efficiency (greater than 99%), discriminating, single-photon devices. While such devices have never been demonstrated, much progress has been made toward their realization [53,54,55,56]. It may be necessary to investigate novel photodetectors based on cavity quantum electrodynamics (QED) and atomic systems; feasible proposals have recently appeared [57,58].

6. The ability to interconvert stationary and flying qubits 🟠

6.1 Optical schemes can interface to solid-state systems via electro-optic devices such as exciton quantum dots. No detailed scheme has been demonstrated that uses such an interface. Some theoretical work has been done on interconverting electronic quantum information to optical entanglement [59,60]. Optical schemes can also interface to atomic schemes, either in high-finesse cavities [61,62] or using "slow-light" schemes in atomic vapor [34].

7. The ability to faithfully transmit flying qubits between specified locations 🟢

7.1 For free-space propagation of photons, this requirement is relatively straightforward to accomplish. However, it is necessary to have well-defined mode structure so that good mode matching can be achieved at beam splitters. In optical fibers, photon loss must be accounted for over distances of more than a few meters; experimentally demonstrated quantum key-distribution protocols give confidence that this is not a serious problem. Implementations that exploit propagation in a photonic band-gap waveguides are possible—but have not yet been demonstrated.

4.0 What Has Been Accomplished

Note: For the status of the metrics of QC described in this section, the symbols used have the following meanings:

a) 🟩 = sufficient experimental demonstration;

b) 🟧 = preliminary experimental demonstration, but further experimental work is required; and

c) 🟥 = no experimental demonstration.

1. Creation of a qubit

1.1 Demonstrate preparation and readout of both qubit states. 🟧

1.1.1 These requirements have been accomplished to some extent using conditional single-photon states from SPDC and post-selection [7,63,64,65]. Precision state tomography has been demonstrated [8]. The first electrically driven single-photon sources (SPSs) were based on a Coulomb blockade effect in a p-n junction [66]. More recently, promising results from single quantum dots have been reported [67,68,69,70]; however, the lowest achieved error (probability of something other than one photon) is still ~60%. Single nitrogen vacancies in diamond have demonstrated photon antibunching, but the output collection efficiency (less than 5%) and large spectral bandwidth (~100 nm) make these unlikely candidates for LOQC [71,72]. Finally, some work has been reported using single atoms in a high-finesse cavity (as in the cavity QED QC schemes); at present the outcoupling efficiency is again only ~8% [73,74].

1.1.2 SPDs with efficiencies of 88% (and predicted to be as high as 95%) have been demonstrated. These detectors have some ability to distinguish incident photon number [53–55]. Superconducting detectors with excellent resolving characteristics have been reported, but their detection efficiency is still low (20%); increases to 80% have been predicted [75].

1.1.3 Suggestions for greater than 99%-efficient detectors with photon-number resolving capability have been proposed, based on coupling to atomic systems [53–56]. Similar schemes for photon quantum memories have been discussed [76]. A simple proof-of-principle optical storage cavity has been demonstrated, reporting storage times of ~50 ns to 1 microsecond [48,49]; technical improvements may increase this to 10s or even 100s of microseconds.

2. Single-qubit operations

2.1 Demonstrate Rabi flops of a qubit. 🟩

2.1.1 Single-photon gates only require a beam splitter with a variable-reflectivity amplitude. For polarization-based dual-rail encoding, single-qubit rotations are easily implemented [77] and performed routinely. A simple feed-forward control has been demonstrated using SPDC [46], as well as a basic quantum memory (photon storage) [48,49].

2.1.2 It would be more difficult to perform a single Rabi flop on a logical qubit encoded in two or more physical qubits in this scheme, although it would depend on how the code was implemented.

2.2 Demonstrate decoherence times much longer than Rabi oscillation.

2.2.1 For a single-qubit gate based on a beam splitter, a huge number of ‘Rabi flops’ (single-qubit rotations) could be performed before dephasing or photon loss become a problem. Similarly, a polarization qubit can be transformed with essentially no decoherence.

2.3 Demonstrate control of both degrees of freedom on the Bloch sphere.

2.3.1 In both interferometric schemes, and also polarization qubit schemes, arbitrary transformations of qubits have been demonstrated. Recently, single-qubit, entanglement-assisted, and ancilla-assisted quantum process tomography [9,10] have been demonstrated [11–14].

3. Two-qubit operations

3.1 Implement coherent two-qubit quantum logic operations.

3.1.1 A nonuniversal two-qubit gate based on SPDC and post selection has been partially achieved [45,47]. In addition, various simple quantum algorithms have been implemented using linear optical systems [23–28,78]. However, much work needs to be done before this is accomplished in a way suitable for scaling. Further progress awaits good SPSs and SPDs. Recently, independently generated single photons (from a quantum dot) were made to demonstrate two-photon HOM interference [79], and independent photons from down-conversion were observed to violate a Bell’s inequality [80].

3.2 Produce and characterize Bell states.

3.2.1 This has already been achieved using SPDC and linear optics [2–8]; however, the methods are based on post selection. A major challenge is to use LOQC methods to generate and characterize Bell states on demand without post selection. This requires SPSs or entanglement-on-demand sources.

3.3 Demonstrate decoherence times much longer than two-qubit gate times.

3.3.1 A typical two-qubit gate may be characterized by the time for photons to propagate through their interferometric gates (less than 1 ns); the time they need to be stored while waiting for a photodetection event (about 50 ns, when all circuitry is accounted for); and the time they will need to be stored while waiting for the next single-photon pulse (still hundreds of nanoseconds). These sorts of storage times are routinely achieved in high-finesse optical cavities.

3.4 Demonstrate quantum state and process tomography for two qubits. 🟩

3.4.1 State tomography for one and two qubits, and process tomography for single-qubit processes has been demonstrated [7,8,11–14,81].

3.5 Demonstrate a two-qubit DFS. 🟩

3.5.1 The optical demonstration of DFSs has been achieved for two qubits [21,22,82].

3.6 Demonstrate a two-qubit quantum algorithm. 🟩

3.6.1 Several simple quantum algorithms have been implemented using optical qubits: Deutsch-Josza [24,25], Grover [23,26], quantum Baker's map [27,28]. While these systems are not scalable, they allow one to investigate the fundamentals of quantum algorithms, and may also allow one to investigate the incorporation of various decoherence-avoidance/correction techniques.

4. Operations on 3–10 physical qubits

4.1 Produce a Greenberger, Horne, & Zeilinger (GHZ) state of three physical qubits. 🟨

4.1.1 This production has already been achieved using SPDC and post selection with linear optics [83]. A major challenge is to generate and characterize GHZ states on demand using LOQC methods and SPSs.

4.2 Produce maximally entangled states of four or more physical qubits. 🟥

4.3 Quantum state and process tomography. 🟥

4.4 Demonstrate DFSs. 🟥

4.5 Demonstrate the transfer of quantum information (e.g., teleportation, entanglement swapping, multiple SWAP operations, etc.) between physical qubits. 🟨

4.5.1 This has been partially achieved using post selection and in the continuous variable system [15–20], but not yet in the LOQC scheme, although the protocols for doing so are well understood.

4.6 Demonstrate quantum error-correcting codes. 🟥

4.7 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza). 🟨

4.7.1 The Deutsch-Jozsa algorithm has been implemented with 3 qubits [24,25]. Also, Grover's search algorithm has been implemented with ~ 10 qubits [26].

4.8 Demonstrate quantum logic operations with fault-tolerant precision. 🟥

5. Operations on one logical qubit

5.1 Create a single logical qubit and "keep it alive" using repetitive error correction. 🟥

5.2 Demonstrate fault-tolerant quantum control of a single logical qubit (DFS work). 🟨

5.2.1 Same as in Section 3.5, above [82].

6. Operations on two logical qubits
    - 6.1 Implement two-logical-qubit operations. ▲
    - 6.2 Produce two-logical-qubit Bell states. ▲
    - 6.3 Demonstrate fault-tolerant two-logical-qubit operations. ▲

7. Operations on 3–10 logical qubits
    - 7.1 Produce a GHZ state of three logical qubits. ▲
    - 7.2 Produce maximally entangled states of four or more logical qubits. ▲
    - 7.3 Demonstrate the transfer of quantum information between logical qubits. ▲
    - 7.4 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza) with logical qubits. This has been achieved for two qubits encoded in a decoherence-free subspace [82]. ▲
    - 7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits. ▲

5.0 Considerations

1. Special strengths
    - 1.1 Well understood physics.
    - 1.2 Very precise single-qubit operations.
    - 1.3 Very low intrinsic decoherence.
    - 1.4 Much off-the-shelf technology is available.
    - 1.5 Directly compatible with quantum communication and scale-up path may be available using planar integrated optics or photonic band-gap technology.

2. Unknowns, weaknesses
    - 2.1 Unknowns
        - 2.1.1 We need a realistic assessment of the resource requirements for a nontrivial implementation (e.g., a five-qubit error correction [or CS5]).
        - 2.1.2 We need a realistic statement of what is possible with (nearly) existing technology.
        - 2.1.3 We should understand the equivalent nonlinearity for a given detection efficiency.
        - 2.1.4 We need to develop the design rules for scaling up an integrated device.
        - 2.1.5 The possible advantages of employing “special” quantum states (e.g., hyperentangled states simultaneously entangled in multiple degrees of freedom, bound entangled states, or maximally entangled mixed states).
    - 2.1 Weaknesses
        - 2.2.1 A reliable, periodic SPS has not been demonstrated.

2.2.2 Discriminating SPDs with demonstrated efficiency >99% have not been demonstrated.

2.2.3 It is difficult to mode-match and stabilize very many, multiply nested, interferometers.

2.2.4 The scheme requires photon detection and fast electro-optic feed-forward control of optical switches on a time scale of nanoseconds. It may become possible to reduce the bandwidth using photon storage.

3. Goals 2002–2007
   3.1 Development of discriminating SPDs with efficiencies greater than 95%.
   3.2 Development of periodic SPSs and entangled multiphoton sources with an error probability per pulse of less than 10%.
   3.3 Demonstration of a 1–10 μs optical quantum memory (to coincide with likely SPS rates).
   3.4 Demonstration of a controlled-NOT (C-NOT) gate that is *not* in the coincidence basis (no post selection) using SPSs.
   3.5 Demonstration of a Bell state on demand, with Bell inequality violation demonstrated *not* in the coincidence basis.
   3.6 Demonstration of a GHZ state on demand with verification *not* in the coincidence basis.
   3.7 Demonstration of a simple error-correction code gate (e.g., loss-detection code, measurement-error code for teleportation gates etc.).
   3.8 Demonstration of a compound gate (e.g., a Toffolli gate).
   3.9 Implementation of a three or four physical qubit (e.g., six or eight mode, three or four photon) processor for a 'test-bed' algorithm (e.g., Deutsch-Jozsa or general error-correction code).
   3.10 Demonstration of a quantum memory compatible with LOQC operation.
   3.11 Demonstration of a coherent state-based scheme for a single C-NOT gate.

4. Goals 2007–2012
   4.1 Development of discriminating SPDs with efficiencies greater than 99%.
   4.2 Development of periodic SPSs and entangled multiphoton sources, with error probability, per pulse, less than 1%.
   4.3 Development of an integrated optical device for a ten logical qubit (e.g., 20 modes, 10 photons) algorithm, incorporating a SPS and a discriminating SPD.
   4.4 Demonstration of a 10-qubit factoring algorithm with error correction.
   4.5 Development of hybrid electro-optic quantum processors that use both solid-state and linear optics for processing.

5. Necessary achievements
   5.1 Develop periodic SPSs with error probabilities less than 1%.
   5.2 Develop discriminating SPDs with efficiencies greater than 99%.

5.3 Demonstration of a C-NOT gate that is *not* based on post selection (i.e., not in the coincidence basis).

5.4 Demonstration of a loss-detection code implementation.

5.5 Demonstration of measurement error-detection code.

5.6 Demonstration of state and process tomography for more than one qubit.

5.7 Demonstration of simple gate operations within an integrated device (optical-fiber or photonic-band-gap device).

6. Trophies

6.1 SPS with 50% probability of success; 90%; 95%; 99%; the mode quality of the source can be verified (e.g., by demonstrating HOM interference with greater than 95% contrast).

6.2 Generate all Bell states via LOQC on demand with fidelity greater than 90% and demonstrate a noncoincidence Bell violation.

6.3 Implement quantum process tomography on more than one qubit.

6.4 High-fidelity (greater than 99%), low-loss (less than 10%; 5%; 1%) optical quantum memory.

6.5 Discriminating SPDs with demonstrated efficiency greater than 90% and a sufficiently low dark-count rate; greater than 99%.

6.6 Loss-detection code or compound-gate implementation.

6.7 Teleportation protocol with greater than 67% efficiency without post selection.

6.8 Teleportation protocol with error-correction code without post selection.

6.9 C-NOT (or some other two-qubit gate) without post selection.

6.10 Generate a maximally entangled N-photon state without post selection.

6.11 Demonstrate process tomography for two-qubit states; three qubits; four qubits.

6.12 Demonstrate a few-qubit quantum memory.

6.13 Demonstrate a fiber-based few-qubit device.
(Note: requires appropriate SPS and discriminating SPD.)

6.14 Demonstrate an integrated few-qubit device.

6.15 Demonstrate a coherent cat-state code.

7. Connections with other quantum information science technologies

7.1 The scheme is close to quantum communication schemes, and the KLM scheme in particular relies on optical quantum teleportation. Because the information already resides in optical modes, an all-optical QC realization might not need to convert the qubits in order to link them to an optical quantum communication scheme. If the quantum communication link relies on telecommunication fibers, it is likely that the wavelength of the qubits will either need to be 1550 nm, or will need to be shifted to 1550 nm to reduce propagation loss. It should also be stressed that optical qubits may be an optimal way to shuffle information from one part of a quantum processor to another even if these main processors are not themselves optically realized. For the case of distributed QC over substantial distances (which promises increased capacity for certain problems), optical qubits are by far the most likely candidate to connect the individual nodes; high-fidelity, high-efficiency wavelength converters will most likely be needed to match the optimal processing wavelength to the optimal transmission wavelength.

8. Subsidiary developments
   8.1 The realization of ultrafast, low-loss electro-optic technologies has direct benefit to future electro-optic quantum communication schemes. Also, reliable quantum memories are a required element of quantum repeater chains, which extend the usable distance for quantum communications (e.g., cryptography and teleportation).
   8.2 The development of brighter, tunable, more robust optical sources of entanglement has a positive impact on quantum communication, and also on (quantum) metrology. It is known that particular quantum states can allow better timing and/or spatial resolution in measurements.

9. Role of theory
   9.1 More theoretical work needs to be done to assess the physical resource requirements for realistic devices (i.e., including photon loss and other sources of imperfect operation).
   9.2 The search for other quantum optical schemes that are simpler to implement should be encouraged. New theoretical tools for the systematic discovery of multi mode conditional gates need to be developed. Only limited work has been done in this area [84].
   9.3 More theoretical work needs to be done on developing optimal fault-tolerant gate implementations.
   9.4 The concept of conditional nonunitary gates needs to be explored in contexts outside of quantum optics whenever good measurements are available. Even if suitable two-particle interactions are available for implementing two-qubit gates, some saving in resources might be made using conditional gates [85] or measurement-induced gates.
   9.5 Scalable devices based on integrated optics and photonic-band-gap devices will require a considerable amount of classical optical modeling.
   9.6 The benefits of employing novel quantum states—hyperentangled states, bound entangled states, etc.—need to be evaluated, as these may reduce the gate complexity or error-correcting code resources.

6.0 Timeline

In a five-year period, we require the demonstration of a few-qubit device. There is some ambiguity as to what would constitute a few-qubit device (particularly when one includes continuous-variable QC). More theoretical work needs to be done to specify a nontrivial, achievable, test algorithm for a three-qubit linear optics implementation that would be a useful technical challenge.

For example, we might propose a *three-qubit device* that can generate any of the eight possible orthogonal entangled states of either GHZ or W class [86], with high fidelity. Another possible test implementation would require an implementation of a three-qubit error-correction code. A three-qubit device would require three photons in six modes in the original code scheme of KLM, plus a number of ancilla modes and ancilla photons. The precise number of ancillas required would depend on the particular implementation and the desired ideal probability of success.

We need to devise a way to quantify the requirements. For example we might ask that the eight orthogonal GHZ or W entangled states are generated with a sufficiently high fidelity, when the algorithm is considered to have worked, (we do not specify the success probability for the ideal implementation) to enable a quantum-communication task to demonstrate a nonclassical correlation without post selection.

To implement the KLM-type scheme, progress is dependent on the availability of SPSs, discriminating SPDs, and optical quantum memories. While such sources are under development, it is difficult to give a firm timeline until such sources are routinely available. However, many proof-of-principle experiments can be done with bright SPDC sources. We will assume that preliminary SPS devices are available by 2004. We also predict that many early implementations may move to fiber-based schemes as a possible entry path to a long-term integrated large-scale device. If low-loss, photonic, band-gap-based technology becomes available, this may be a likely candidate over fiber—if it is shown to be more stable and robust. As they can reduce the gate complexity, entangled-photon sources should continue to be developed. Finally, work is needed to understand the possible benefits of using hybrid sources (qubit + continuous variable, or simultaneous entanglement in multiple degrees of freedom).

1. Timeline for 2002–2007
    - 1.1 SPS and SPD development
        - 1.1.1 Development of a prototype SPS with error probability, per pulse, of less than 50% (where error is either zero or more than one photon per pulse).
        - 1.1.2 Continued development of multiple, bright SPDC sources, including hyperentangled sources.
        - 1.1.3 Development of robust SPSs, with error probability, per pulse, less than 10%.
        - 1.1.4 Development of photon-entanglement on-demand source, with error probability, per pulse, less than 10%.
        - 1.1.5 Development of novel discriminating SPDs with high efficiency (e.g., quantum memories run as photon detectors, cavity-QED schemes).
        - 1.1.6 Incorporation of a SPS into a quantum interferometer (HOM)—greater than 95% contrast should be achieved.
        - 1.1.7 Development of high-fidelity (greater than 99%), high-efficiency (greater than 90%) wavelength shifters, if needed to match optimized sources and detectors.
    - 1.2 Measurement and control
        - 1.2.1 Optimization of prototype detectors for high efficiency.
        - 1.2.2 Sustained development of other novel SPD schemes with high efficiency.

1.2.3 Development of fast electro-optic, feed-forward delay lines for quantum memory and other control circuits for optical teleportation without post selection.

1.2.4 Development of automated multiqubit, quantum state and process tomography systems.

1.3 Basic LOQC

1.3.1 Theory: realistically assess resource overheads for a three-qubit (six-mode) linear optical quantum processor for a test-bed task such as generating a CS code teleportation resource (see KLM), or a GHZ or W state (not in coincidence basis) including required reliability of the SPS and detector efficiency.

1.3.2 Theory: develop experimentally relevant schemes (tomography or another scheme) for determining multimode entanglement of photon-number states.

1.3.3 Theory: determine benefit of using hybrid sources (qubit + continuous variable), or simultaneous multiparameter entanglement.

1.3.4 Demonstration device using SPDC sources (e.g., C-NOT in coincidence basis) using fiber-based interferometers.

1.3.5 Implementation of teleportation with loss-detection code (e.g., see KLM article, Figure 4) using SPDC.

1.3.6 Implementation of the nondeterministic $\text{C-NOT}_{1/4}$ teleportation gate in the coincidence basis, using a single very bright SPDC source or two or more multiplexed SPDC sources (requires eight modes and four photons).

1.3.7 Implementation, using SPSs, of a C-NOT gate *not* in the coincidence basis to generate arbitrary Bell states on demand and demonstrate a noncoincidence Bell violation.

1.3.8 Implementation of a three- or four-qubit (six- or eight-mode, three- or four-photon) processor for a 'test-bed' algorithm (to be determined).

1.3.9 Demonstration of a quantum memory compatible with LOQC operation.

2. Timeline for 2007–2012

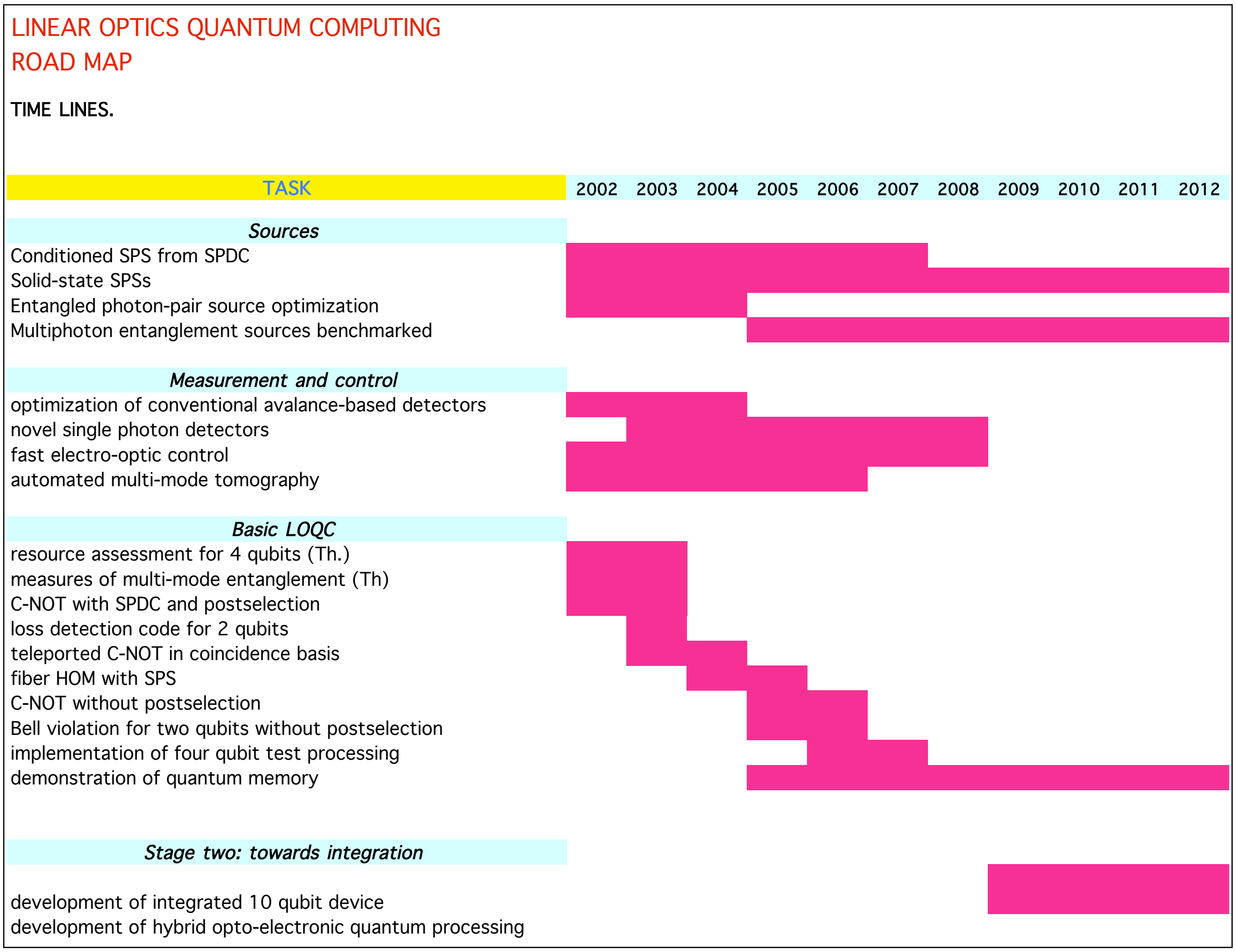
2.1 Develop discriminating SPDs with efficiencies greater than 99%.

2.2 Develop periodic SPDs and entangled multiphoton sources, with error probability, per pulse, less than 1%; demonstration of full entanglement swapping.

2.3 Development of 99%-efficient quantum memory.

2.4 Develop an integrated optical device for a 10-qubit (20 modes, 10 photons) algorithm, incorporating a SPS and a discriminating SPD as integral components.

2.5 Develop hybrid electro-optic quantum processors that use both solid-state and linear optics for processing.



LINEAR OPTICS QUANTUM COMPUTING
ROAD MAP

TIME LINES.

TASK	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Sources											
Conditioned SPS from SPDC	■	■	■	■	■	■					
Solid-state SPSs	■	■	■	■	■	■	■	■	■	■	■
Entangled photon-pair source optimization	■	■	■								
Multiphoton entanglement sources benchmarked				■	■	■	■	■	■	■	■
Measurement and control											
optimization of conventional avalance-based detectors	■	■	■								
novel single photon detectors		■	■	■	■	■	■				
fast electro-optic control	■	■	■	■	■	■	■				
automated multi-mode tomography	■	■	■	■	■						
Basic LOQC											
resource assessment for 4 qubits (Th.)	■	■									
measures of multi-mode entanglement (Th)	■	■									
C-NOT with SPDC and postselection	■	■									
loss detection code for 2 qubits		■									
teleported C-NOT in coincidence basis		■	■								
fiber HOM with SPS			■	■							
C-NOT without postselection				■	■						
Bell violation for two qubits without postselection				■	■						
implementation of four qubit test processing					■	■					
demonstration of quantum memory				■	■	■	■	■	■	■	■
Stage two: towards integration											
development of integrated 10 qubit device								■	■	■	■
development of hybrid opto-electronic quantum processing								■	■	■	■

Figure 6-1. Optical QC developmental timeline

7.0 Glossary

Single-photon source (SPS)

A transform-limited pulsed optical field with one and only one photon per pulse. The pulses must exhibit first-order coherence (i.e., must exhibit self interference) and must enable two-photon interference (e.g., HOM interferometer [51]) using a delay line.

Discriminating single-photon detector (SPD)

A photon counter that detects one or more photons with high efficiency and can robustly discriminate between 0, 1, 2, or more photons.

Spontaneous parametric down conversion (SPDC)

The current method of choice for producing pairs of correlated photons. A high-frequency photon is split into two lower-frequency daughter photons via a nonlinear optical crystal. In addition to being able to directly create polarization-entangled pairs, several groups are pursuing it as a means to realizing a SPS.

Linear optics

Any optical device that is described by a Hamiltonian which is at most quadratic in the field amplitudes. Such devices include phase-shift components, mirrors, beam splitters, and polarizers. The class may be extended to include devices that make use of the second-order susceptibility in which one of the fields is classical (e.g., parametric down conversion with a classical pump field). As the Hamiltonian for a linear optical device is, at most, quadratic in the field amplitudes, the resulting Heisenberg equations of motion are linear in the field amplitudes.

HOM interferometer

A quantum interferometer, first implemented by Hong, Ou, and Mandel [51], in which single photons enter each of the two input ports of a 50:50 beam splitter. The probability for coincidence counts at the two output ports is zero when temporal and spatial mode-matching is perfect. This is the required test of a SPS intended for LOQC. Also, the HOM interferometer is useful for polarization Bell-state analysis, as required (e.g., in quantum dense coding and teleportation).

GHZ (Greenberger, Horne, and Zeilinger) and W states.

There are two classes of entangled states for a three-qubit system in the sense that a state in one class cannot be transformed into a state in the other class by local operations and classical communication (LOCC) [86]. There are two orthogonal GHZ states (with the form $|000\rangle \pm |111\rangle$) and six orthogonal W states (with the form $|001\rangle \pm |010\rangle \pm |100\rangle$). The GHZ states are pure states specified by the correlation "all qubits have the same value." The W states are specified by the correlation "any two qubits are correlated."

Quantum state and quantum process tomography

In quantum state tomography, a number of measurements are made on an ensemble of identically prepared quantum systems. If the Hilbert space is of finite dimension, then a finite number of measurements suffices to allow one to reconstruct the quantum state of the particles [8]. Quantum process tomography uses similar techniques to characterize a quantum process, e.g., a unitary transformation, decoherence, etc. [9,10]. This means the effect on any possible input state to the process may be predicted.

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